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Wind Farm Power Fluctuations, Ancillary Services, and System Operating Impact Analysis Activities in the United States

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WIND FARM POWER FLUCTUATIONS, ANCILLARY SERVICES, AND SYSTEM OPERATING IMPACT ANALYSIS ACTIVITIES IN THE UNITED STATES

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ABSTRACT: With ever increasing penetration of wind capacity and growing interest in wind power by electric utilities and other power providers, questions about the impacts and costs associated with maintaining a stable grid is receiving lots of attention. These issues are important, both in competitive and regulated monopoly markets.

To evaluate the range of ancillary service impact of wind power plants, wind power plant output fluctuations on the order of seconds to minutes must be known. However, the data required for a credible analysis has not been widely available. The National Renewable Energy Laboratory (NREL), through its own efforts, and in conjunction with a wide group of stakeholders including other national labs, consultants, developers, utilities, and the non-profit Utility Wind Interest Group, has initiated measurement and analysis activities.

The efforts are ongoing. While final system-cost results are not available, this paper will describe the progress to date and present typical results and statistical analysis. In addition, methods will be explained with the aim of soliciting feedback from others looking at similar issues worldwide.

Keywords: Wind Farm, Power, Statistics

1 INTRODUCTION

Wind power installation has increased steadily in the past 20 years, both in the United States and throughout the world. In terms of growth rate, wind power has become the fastest growing energy source in the world. With continued research and development to improve wind turbine performance, various policies to encourage the deployment of renewable energy, and escalating fossil-fuel prices, this trend is expected to continue. Because of these developments, more utilities today are seriously examining the wind option.

Many utilities in the United States have expressed concerns over installing large-scale wind power plants in the electric power system. The intermittent nature of the wind resource, together with short-term power fluctuations, are the two principal issues facing a utility with wind power plants in its power system. Power fluctuations may affect the operations of the electric power system. It may also impact wind power's participation in the bulk-power market by affecting its ancillary-services requirements in a competitive business environment. Real wind-power data would also allow researchers to investigate the extent of wind power's spatial and temporal diversity, as well as capacity credit issues. Despite these concerns, and despite the need for using long-term, high-frequency, real wind-power plant output data to analyze the impacts, in the past there were no programs in the United States to systematically collect such data.

NREL, together with other stakeholders, has initiated wind power measurement and analysis activities to remedy these situations. While these efforts are still ongoing, some data are available for analysis. This paper describes the results to date. In addition, it outlines the context and use of the anticipated results.

1.1 Wind Power Data Measurement

To evaluate the short-term power fluctuations of large wind power plants and assess wind power's ancillary-services burdens (or benefits), NREL entered into an agreement with Enron Wind Corporation (EWC) for long-term monitoring of wind power output at the Lake Benton II plant near Ruthton, Minnesota. The Lake Benton II plant has 138 Zond Z50 turbines, each rated at 750 kilowatts (kW). The plant's total wind-power-generating capacity is 103.5 MW. Four 34.5-killivolt (kV) lines collect and feed the wind power into the local utility's nearby 115-kV transmission network through a substation. Data-recording equipment was installed at these four 34.5-kV interconnection points to collect read power, reactive power, phase voltages, and wind speed. All data are recorded at a rate of 1 Hertz (Hz). The data set from this wind power plant began in February 2000.

NREL has also contracted with a private firm to collect wind power output data from two other locations for this monitoring project. One is a large wind power plant located in northwestern Iowa near Storm Lake, which has 262 Zond Z50 turbines. The total installed wind power capacity is 196.5 MW. The output from 151 turbines (113.25 MW) is monitored under the contract. In addition to real and reactive power, phase voltages, and wind speed data at 1 Hz, wind direction information is also recorded. Data from Storm Lake have been available since January 2001. The other location is a substation called Buffalo Ridge, located in southwestern Minnesota. There are several wind power plants of varying size in this area. Approximately 220 MW of wind generating capacity is connected to the Buffalo Ridge substation, where data monitoring is taking place. Most of the wind turbines in this area are Zond Z50 turbines. There are also a small number of Micon 750-kW and Vestas 660-kW turbines. Data from this site began in mid-February 2001. The contract requires at least two years data from both sites.

1.2 Data Analysis

NREL staff members are analyzing the collected data to examine wind power fluctuations. Two measures are used to gauge the extent of power level fluctuations: step changes and ramping rates. Step changes (the differences in output power levels between consecutive time steps) show all the values of instant changes the plant can experience. They establish a boundary of power level changes for large wind power plants. Simple statistics of all step-change values reveal the distribution of all the values. Table I lists the maximum positive (increase in output power) and negative (decrease in output power) values of Lake Benton II during the 12-month period (February 2000 to January 2001) for three time steps: 1 second, 1 minute, and 1 hour. It also lists their average values and standard deviation values. To focus on only the maximum power changes caused by decreasing or increasing wind speed, we screened the recorded data stream to eliminate power changes caused by forced or controlled outages and startups.

Table I. Maximum, Average, and Standard Deviation of Lake Benton II Step Changes

	Maximum Positive (kW)	Maximum Negative (kW)	Average (kW)	Std. Dev. (kW)
1-second	4,430	-7,590	0	168
1-minute	11,541	-14,304	0	1,103
1-hour	65,410	-51,653	-56	10,220

It is clear that, for short periods, the step changes are very small. The maximum increase in power is 4,430 kW, or 4.3% of the nameplate capacity (in 1 second), during this 12-month period. For 1 minute, the maximum increase in power is 11,541 kW, or 11% of the nameplate capacity, which is equivalent to a sustained ramp-up rate of 192 kW per second, or 0.2% of the rated power per second. The maximum 1-second step drop is 7,590 kW, or 7.3% of the nameplate capacity. For the same period, the maximum 1-minute step drop is 14,448 kW, or 14.0% of the nameplate capacity. This is equivalent to a sustained ramp-down rate of 241 kW/s, which is much smaller than the maximum 1-second step-change value.

Wind speed can change substantially in an hour, and hourly power changes can be very large. The maximum 1-hour increase during the 12-month period (from February 2000 to January 2001) is 65.4 MW (63% of total capacity), and the maximum 1-hour decrease is 51.7 MW (50% of total capacity). In terms of kW per minute, this is equivalent to 1,090 kW/min and -860 kW/min, respectively; both are much less than the maximum 1-minute changes. However, those maximum values in either direction occur only infrequently. Figure 1 shows the distribution of step-change values for different time step sizes. It confirms that power level changes are confined in a narrow range.

To investigate sustained power changes, we calculated ramping rates in either direction for various periods. The ramping rates discussed here are slopes of a straight line used to fit the wind-power data points. Table II lists the ramping rates in kilowatts per second calculated with 1-second power data in three time intervals: 5, 10, and 15 seconds, and kilowatts per minute calculated with 1-minute average power data for two time intervals: 5 and 10 minutes.

Table II. Ramping Ratings

	Positive Ramping Rates		Negative Ramping Rates	
	Average	Std. Dev.	Average	Std. Dev.
5-second (kW/s)	37	49	-41	88
10-second (kW/s)	28	37	-31	65
15-second (kW/s)	24	32	-26	54
5-minute (kW/min)	320	530	-343	723
10-minute (kW/min)	264	426	-278	509

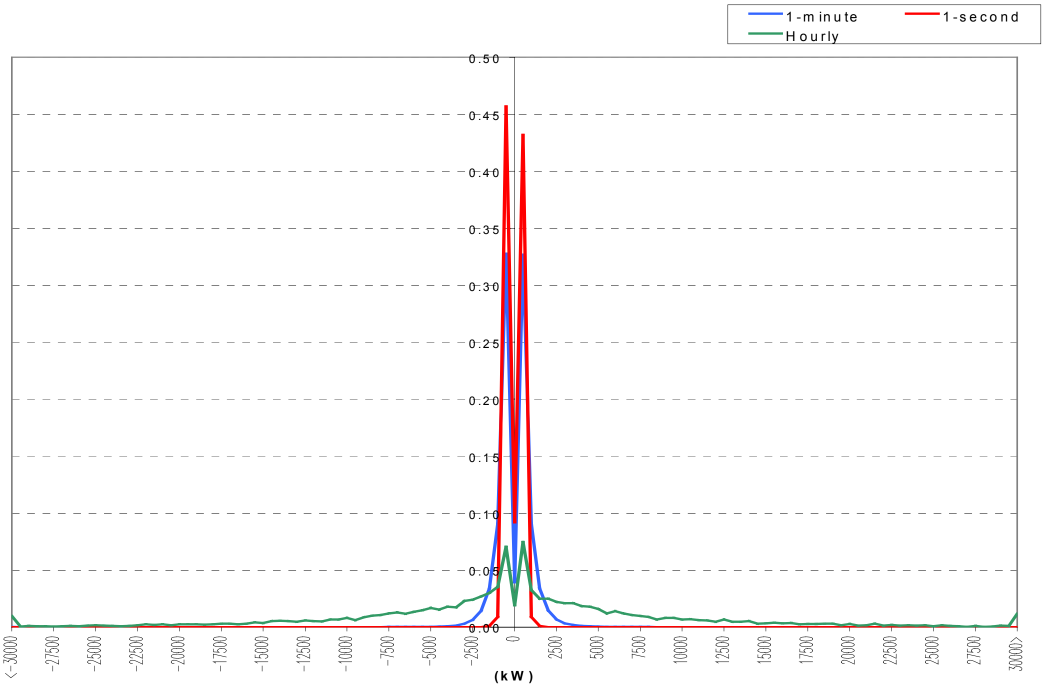

Figure 1. Distribution of step changes

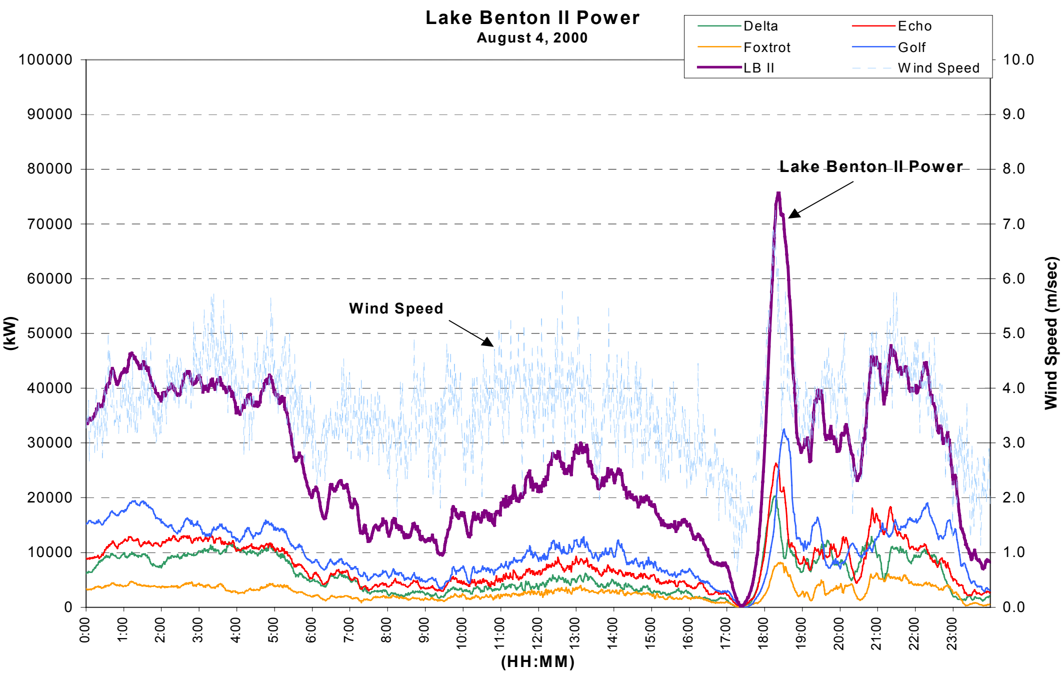

Figure 2. Wind power plant daily production profile

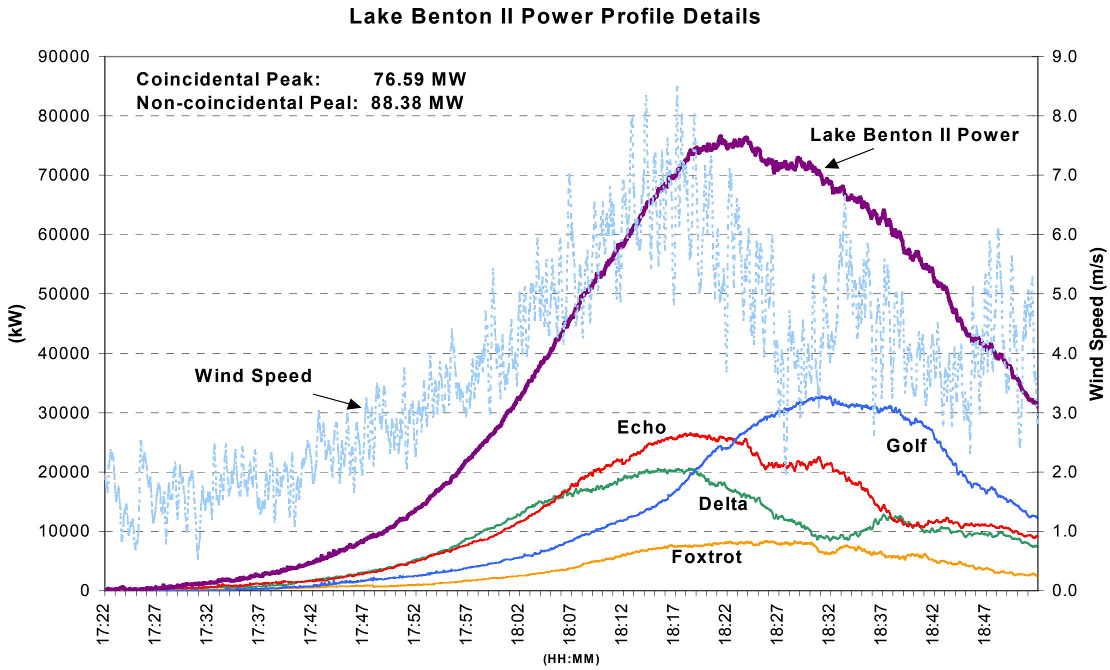

Figure 3. Power profile details

For 5-second, 10-second, and 15-second intervals, the average values for both the ramping-up and ramping-down rates are much smaller, with a magnitude of 37 kW/s and 41 kW/s, respectively. They are less than 0.04% of the total capacity per second. As expected, longer time intervals always result in lower ramping-up and ramping-down rates. Ramping rates calculated with 1-minute average power data show a similar pattern with small average values—less than 0.4% of total wind power plant capacity per minute. The small standard deviation values of ramping rates also indicate that short-term ramping rates are both small and confined within a narrow range.

The distribution of ramping rates shows that, for 5-second intervals, 90.3% of the apparent ramping rates are within ±100 kW/s. For 10-second intervals, 94.9% of apparent ramping rates are within ±100 kW/s, and for 15-second intervals, 96.8% are within ±100 kW/s. For longer times, the ranges are even narrower. For 5-minute intervals, 90% of apparent ramping rates are within ±780 kW/min (or 13 kW/s). For 10-minute intervals, 90% of apparent ramping rates are within ±640 kW/min (or 11 kW/s). These results suggest that if another power plant were to be dedicated to regulate the output of Lake Benton II, the duty requirement for the dedicated power plant will be ±220 kW/s (or about 0.2% of the total installed capacity per second). This range would cover 99% of all apparent ramping rates for Lake Benton II.

The 138 turbines at Lake Benton II are arranged along a northwest-to-southeast diagonal line about 17 kilometers (km) (10.6 miles) long. The turbine operations are not synchronized, and their outputs do not rise and fall at the same time. When a wind gust sweeps through the site, it reaches some turbines sooner than others. If we monitored the output of every turbine, we should detect an output with a wave-like pattern. However, even with data from only four interconnection points, this effect is still detectable.

An example of this effect is given in Figure 2, which shows output profiles of the four grid-interconnection points and their sums for a summer day in 2000. They are plotted with 1-minute average power data. The graph shows that although the outputs from all four grid-interconnection points generally follow the wind speed, they are not locked in exact step. An event later in that day highlights these phenomena. Shortly after 17:30, a gust passed through the site, resulting in a power surge of 75 MW in about an hour (a ramp rate of 1.3 MW/min. or 21 kW/s). It is clear from the graph that not all four grid-interconnection points rise to their peak power at the same time. Figure 3 shows the details of the gust and power surge in a 90-minute window (from 17:22 to 18:51) plotted with 1-second power data from these four interconnection points and their sum.

The effect of wind turbine separation is very clear in the detailed power profile plot. The non-coincidental peak during this 90-minute period (the sum of the four individual peaks in the period) is 88.38 MW if the same gust would have hit all turbines at the same instant. However, the turbines are scattered, and it takes time for the gust to sweep through them. When power from the Golf interconnection point begins to rise, power from the Delta interconnection point has already begun to drop. Therefore, the coincidental peak during this 90-minute period is only 76.59 MW. The coincident factor for this 20-minute period is 0.887.

Another way to examine the variability of the wind speed at different sites is to look at the coefficient of variation (COV), which is the ratio of the standard deviation of wind speed to the mean wind speed. The COV of wind speed is known as the turbulence intensity of wind. A higher COV indicates more turbulent wind and more wind-power fluctuations. However, a wind power plant with many turbines will attenuate the resulting output power fluctuations. Obviously, this output leveling effect is more prominent with an increasing number of turbines and with a greater distance between the turbines.

Available power in the wind is proportional to the cube of the wind speed. If the COV is calculated with wind speed cubed, and the result compared to the calculated COV of measured power from the wind plant, a pattern of much-reduced variability emerges. Table III shows the COV values of wind speed cubed and power output at the Echo interconnection point, as well as the entire wind power plant. The reduction in variability is very clear. On average, the variability of power output is only about half the variability of wind speed cubed.

Table III. COVs of Wind Speed Cubed and Wind Power

	$(m/sec)^3$	Echo kW	LB II kW	Storm Lake kW	LB II & Storm Lake kW
1-second data	1.91	0.912	0.896	0.855	0.616
1-minute average	1.87	0.911	0.897	0.855	0.616
10-minute average	1.82	0.908	0.894	0.854	0.615

Table IV. Hourly Energy Production and Regulation Standard Deviation (MW)

January 2001	**Minimum**	**Average**	**Maximum**
Hourly Energy Production	0.0	46.4	99.2
Hourly Regulation Standard Deviation	0.0	1.13	8.06

The columns of wind speed cubed, Echo power, and Lake Benton II power COVs in Table III are calculated with 12 months of data (from February 2000 to January 2001). Columns of Storm Lake power and combined Lake Benton II and Storm Lake power are calculated with data from the first two months of 2001. The reduction in variability is very clear. On average, the variability of power output is only about half the variability of wind speed cubed. When outputs from more wind turbines are included in the calculation, the reduction in power variability becomes more prominent. Table III shows that when calculations are extended to the combined output of Storm Lake and Lake Benton II, the result is another 20% reduction in power level variability.

1.3 Hourly Analysis of Regulation Requirements

Electricity consumption and prices vary dramatically throughout the day. Energy markets typically clear hourly. Ancillary service requirements for individual customers and for the power system as a whole vary hourly as well. To facilitate the integration of wind into electricity and ancillary service markets, it is useful to examine how regulation requirements and energy production vary over time frames that are shorter than a month. Table IV provides average hourly statistics for January 2001.

As expected, there is considerable range to both energy production and regulation. Figure 4 further illustrates this point by showing both energy production and regulation requirements for the month.

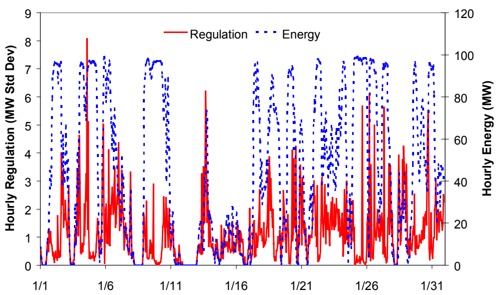

Figure 4. One month of hourly energy and regulation, January 2001

Clearly, both energy production and regulation requirements are volatile, but they do not appear to be coincident. Figure 5 provides a closer view of three days where it can be seen that the regulation requirement and energy production requirements are related but not coincident. The relationship between energy production and regulation requirement is further explored in Figure 6, where the regulation requirement is plotted against the energy production for all 744 hours in the month. This plot shows significant scatter. Fitting a curve to the data does show some pattern, however. As might be expected, the regulation requirement tends to be slightly higher in the middle of the energy production range than it is at either very low or full production. This might be expected because there is very little output variability when the wind is not blowing. Similarly, once the wind machine has reached full output it cannot produce more output even if the wind increases. So the regulation requirement tends to be highest at mid-energy production.

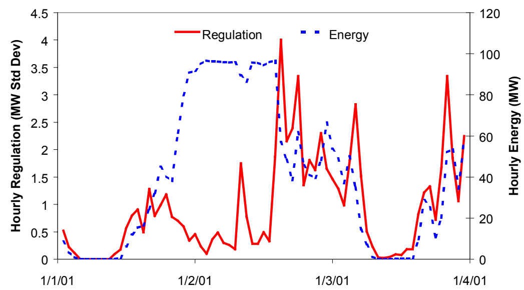

Figure 5. Three days of hourly energy and regulation, January 2001

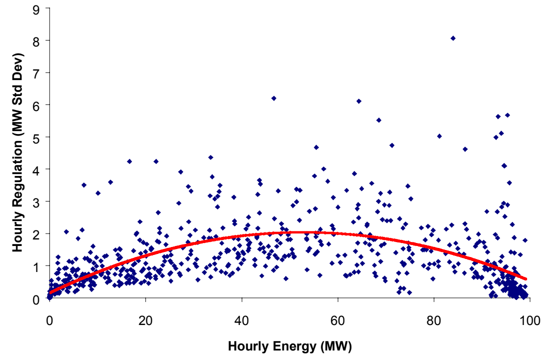

Figure 6. Regulation and energy consumption, January 2001.

It is also instructive to examine how persistent the regulation requirement is. Figure 7 presents a regulation-duration curve. It shows that the regulation requirements are high for a relatively short time. Contrast the wind regulation duration curve with Figure 8, which presents similar curves for a steel mill, a set of non-industrial loads, and an entire utility. The steel mill and the other conventional loads present regulation burdens that are much more uniform: they are constantly requiring compensation by regulating generators. A wind plant's regulation requirements appear to be more sporadic.

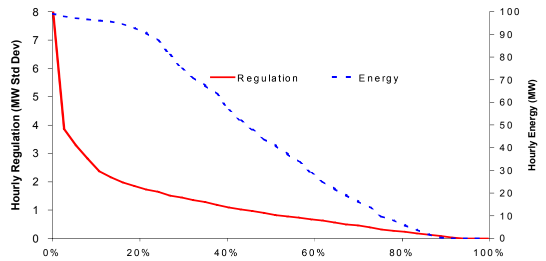

Figure 7. Energy and regulation duration, January 2001

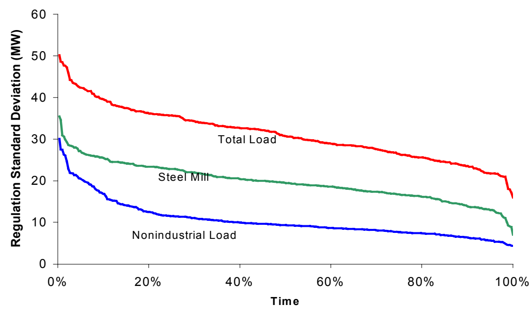

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Figure 8. Load and regulation requirements

Wind plants will have to interact with both energy and regulation markets somewhat independently. The timing of those interactions will be important.

RELATED ACTIVITY

In addition to works done by NREL and ORNL, Utility Wind Interest Group (UWIG) has started a project to study the impacts of significant wind generation facilities on bulk power system operations, scheduling, and operations planning. The project will use actual wind speed and wind power data in utility-specific case studies to quantify costs and benefits of large wind power plants in utility power system. Wind power plant operating issues such as frequency control, regulation, load following, scheduling and unit commitment will be examined in the UWIG project.

CONCLUSIONS

As mentioned earlier, the wind farm monitoring and data analysis projects are still ongoing.

1. Statistics of the actual wind power data show that power fluctuations caused by wind-speed variations--although stochastic in nature--are neither extreme nor completely random in terms of their magnitudes and change rates (ramping rates).

2. Spatial diversity exists within a single wind-power plant, and it reduces variations of wind power. The effect is more noticeable with bigger plants (more turbines and wider separation) or in plants that are tens or hundreds of miles apart.

3. The results show that when wind power is integrated into a utility grid, the regulation burden attributed to the wind-power plant is influenced by the relative magnitude of the pre-existing variation (e.g., regulation burden caused by loads). In cases where the variation of the plant's output is small relative to the pre-existing grid load variation, the regulation impact of the wind power plant will be quite small.

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